High-Frequency Acoustic Propagation in Shallow, Energetic, Highly-Salt-Stratified Environments

Andone C. Lavery
Department of Applied Ocean Physics and Engineering
Woods Hole Oceanographic Institution
Bigelow 211, MS 11
Woods Hole, MA 02543
telephone: (508) 289-2345 fax: (508) 457-2194 email: alavery@whoi.edu

David Farmer
The Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882
telephone: (401) 874-6222 fax: (401) 874-6889 email: dfarmer@gso.uri.edu

Award Number: N00014-11-10058
http://www.whoi.edu/people/alavery

LONG-TERM GOALS

The long term goal of this research is to measure and understand high-frequency, line-of-sight acoustic propagation in an estuarine environment characterized by strong tidal flow, often large salinity stratification, high shear, high dissipation rates of turbulent kinetic energy, shear instabilities, and increased water property variability.

OBJECTIVES

Acoustic propagation techniques provide a means for remote-sensing of the path-averaged statistical structure and motion of the intervening flow, providing information on the 2-dimensional characteristics of turbulence, microstructure, and advection. Estuaries provide an excellent environment to quantify stratified turbulence and its influence on acoustic propagation as a broad range of stratification and turbulence intensities are encountered within a single tidal cycle.

The primary objective is to conduct high-frequency (120 kHz), line-of-sight acoustic propagation measurements from 29 October to 2 November, 2012 in the Connecticut (CT) River estuary. In addition, measurements of high-frequency broadband acoustic backscattering (30 – 600 kHz), currents (using a 1.2 MHz ADCP), suspended sediment concentrations, fluorescence, and continuous conductivity, temperature, and depth (CTD) measurements will be performed in order to support the interpretation of the scintillation data. Secondary objectives include testing the validity of the existing theoretical framework for propagation of high-frequency sound through a highly turbulent medium,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2012**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **High-Frequency Acoustic Propagation in Shallow, Energetic, Highly-Salt-Stratified Environments**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Applied Ocean Physics and Engineering Woods Hole Oceanographic Institution Bigelow 211, MS 11 Woods Hole, MA 02543**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

determining the range of conditions under which it is accurate, and quantifying the importance of anisotropy.

APPROACH

Decades of research has shown that the propagation of sound waves through a moving random medium, such as the atmosphere [1] or the ocean [2], provides a means for remote-sensing of the path-averaged statistical structure and motion of the intervening fluid medium. These techniques, however, have been less exploited at high acoustic frequencies and over short ranges, applicable in shallow coastal waters, where there can be highly variable fluid flows, with intermittent strong mixing and high stratification, depending on the tidal cycle, wind, currents, and topography. Under these conditions, it is typical to encounter regimes of homogenous and isotropic turbulence, and for propagations distances over which the Rytov approximation holds, it is possible to infer path-averaged turbulence parameters using Tatarski's weak scattering theory. Though there have been a number of theoretical and numerical studies [e.g. 3, 4] that apply these techniques to investigating turbulence in shallow waters, and its influence on acoustic propagation, there have only been a handful of measurements performed [e.g. 5], with a focus on relatively unstratified conditions.

The high-frequency, line-of-sight acoustic scintillation measurements that are the core of this project will be performed in the CT River, a highly-salt-stratified estuarine environment and should provide the framework for a better understanding the complex problem of high-frequency sound propagation in shallow, highly-stratified, highly-energetic environments, and for setting bounds on the range of validity of Tatarski's weak scattering theory. Quantifying and understanding the influence of turbulence on high-frequency acoustic propagation, for example quantifying the times scales of variability, is particularly important in the context of recent developments in the area of high-frequency, shallow-water, acoustic communications, as well as being particularly relevant to the development of acoustic observatories. Acoustic observatories provide a powerful remote-sensing technique for real-time long-time-series monitoring of transport, mixing, and circulation patterns in coastal regions. Measurements of turbulence and microstructure in the ocean are usually performed with high-spatial resolution instruments, such as ADVs, shear probes, or fast-response thermistors and conductivity sensors. However, these are time-consuming, point measurements, which can be influenced by local inhomogeneities and may not be representative of the mean flow. In contrast, high-frequency acoustic propagation techniques average over local anomalies along the transmission path and can provide information not only on path-averaged dissipation rates of turbulent kinetic energy but also on mean flows.

The measurements involve the use of a reciprocal transmission acoustic scintillation system to extend existing high-frequency acoustic propagation techniques [5-8] to study the 2-dimensional (2-d) characteristics of advection, microstructure, stratified turbulence, and turbulence anisotropy, in shallow salt-stratified estuarine environments. Of particular interest are 1) the effects of turbulence anisotropy on the effective refractive index fluctuations, as the refractive index fluctuations can be related to turbulence parameters, such as the dissipation rate of turbulent kinetic energy, under some conditions, 2) the presence and influence of coherent 3-D wave structures and shear instabilities generated in highly sheared, high-Reynolds number environments [9,10].

The measurements will be conducted with a cabled, acoustics propagation system with real-time data-collection capabilities (Figure 1). The system consists of two, 120-kHz, 4-transducer, 1m^2 square acoustic arrays mounted on tripods 3 m above the bottom (Figure 2). The tripods will be separated by approximately 50 meters. The novel and key capability of this system is that every transducer has both transmitting and receiving capabilities, allowing forward and reciprocal acoustic transmissions along 16 different paths. The measurements will combine acoustic scintillation, two-dimensional angle of arrival fluctuations, and reciprocal transmission techniques:

<u>Acoustic scintillation</u>: Acoustic scintillation refers to the accumulation of the effects of the continuously evolving amplitude and phase of the acoustic waves as they propagate through a fluctuating medium. Mean fluid motion [5], turbulent velocity fluctuations [6], and temperature and salinity fluctuations [8] contribute to the forward scattering of high-frequency acoustic waves and thus to the variability in the effective refractive index of the fluid. Measurements of acoustic scintillation, in combination with an understanding of the theoretical framework of acoustic propagation through a turbulent medium, can be used to infer path-averaged parameters of intervening turbulence. In addition, measurements of acoustic scintillation allow the mean current flow perpendicular (cross-path) to the acoustic propagation path to be determined by exploiting the coherence of fine-structure advected across two closely spaced horizontal transducers [5].

<u>2-dimensional angle of arrival</u>: Using the tomographic array of acoustic transducers, properties of the 2-dimensional arrival angle can be related to the properties of the 2-d turbulent flow, allowing turbulence anisotropy to be investigated [7]. The scatter in the angle of arrival fluctuations is related to the intensity of the refractive index fluctuations, which are related to the path-averaged turbulent kinetic energy, if velocity fluctuations dominate over, or can be separated from, temperature and salinity fluctuations using reciprocal transmission techniques.

<u>Reciprocal transmission</u>: Reciprocal transmission can be used to separate the effects of ocean currents on acoustic propagation from the effects of sound speed structure, and to separate the contribution to scattering from velocity fluctuations and temperature and salinity fluctuations. The high-frequency acoustic propagation array will be used to obtain measurement of the following path-averaged properties of the flow:

1) the component of horizontal flow resolved along the acoustical path (though this is expected to be small in this particular experiment due to the experimental set-up), derived from reciprocal transmission,
2) the horizontal component of flow perpendicular to the acoustic path, derived from acoustical scintillation drift,
3) the vertical shear, derived from (1) and (2) for vertically separated depths,
4) the mean density at the depth of each acoustical path, using the two-way travel time to get sound speed, together with an independent measure of the T-S relationship,
5) the bulk Richardson number, from (2) and (4),
6) the dissipation rate of turbulent kinetic energy at each depth, using reciprocal transmission analysis, and

7) the degree of turbulence anisotropy, using 2-dimensional angle of arrival techniques, and again using reciprocal transmission to separate the contribution of vector and scalar components. Turbulence anisotropy is expected to be most pronounced when the there is significant mean vertical shear.

The proposed site for the measurements is the Connecticut (CT) River estuary, south of the Amtrak Railroad bridge (Figure 3). The field measurements will be performed from 29 October to 2 November, 2012, encompassing multiple tidal cycles, with different degrees of turbulence intensities generated throughout any given tidal cycle (Figure 4). The choice of the CT River is motivated partly by the physics of the flow (highly stratified and energetic), as well as by the potential for capitalizing on the research already conducted at this location (measurements funded in part by ONR Physical Oceanography in 2008 and 2009). These previous field measurements were focused on measuring and understanding high-frequency broadband acoustic backscattering in highly-stratified, energetic estuarine environments together with direct microstructure measurements [9,10]. The measurements already performed at this field site provide significant insight into the expected flow regimes, with shear instabilities representing a dominant mechanisms leading to mixing during certain times of the ebb tide (Figure 5), and potentially leading to significant variability in the scintillation arrivals. The broadband acoustic backscattering system (30-600 kHz) will be deployed in close proximity to the scintillation system path in order to provide information on microstructure and structure of shear instabilities: specifically, it will be deployed 20 m south of the scintillation system path (downstream during the ebb tide). In order to address questions relating the 3-D structure of the shear instabilities the 6 broadband transducers that comprise the backscattering system will be separated to span a 6 m array (Figure 6). A 1.2 MHz ADCP will also be mounted on the backscattering array to measure velocity and to enable shear to be inferred, as well as a CTD (sampling at 16 Hz) and a fluorometer. All operations will be performed from the RV Connecticut (based out of Avery Point, CT), a 76 foot vessel with dynamic positioning, which will also serve as floating laboratory and be on-site for the duration of the experiment. Continuous vertical CTD profiles will also be performed in order to measure water column characteristics.

WORK COMPLETED

1. ***Scintillation System Hardware and Software Upgrades.***
   The scintillation system was originally deployed during the SPACE08 experiment. In the SPACE08 configuration, all electronics were located underwater on tripods. Significant hardware and software modifications have been completed in order to allow the electronics to be updated and to ensure that the electronics are now no longer housed underwater on the tripods. This allows modifications to made on the fly in response to changing flow parameters. The transducers have also been replaced with high quality transducers and the cables have been made longer for shore- or vessel-based operations. In addition, new modular tripods have been constructed that allow easy transportation to the CT River field site and are robust enough to withstand the typical currents encountered in the CT River. The modifications to the scintillation system hardware and software have been performed by Ron Teichrob and Svein Vagle in Sidney, BC. Andone Lavery spent one week in June 2012 testing the system. The system is currently being shipped to WHOI for final assembly and testing prior to the deployment in October 2012.

2. ***Logistics.***
   Two one-day reconnaissance trips to the CT River were undertaken in June 2011 and August 2012 to assess the best location for deployment of the scintillation system, balancing both the scientific needs and logistical difficulties, as well as to determine the influence of different discharge regimes on the observation of shear instabilities.
3. ***Modeling.***
   Modeling of the acoustic propagation eigenrays based on the CTD data collected in the CT River in 2009 is underway in order to determine the best signals to be used during the upcoming experiment.
4. ***Permitting.***
   The Coast Guard, the Army Corps of Engineers, and the State of Connecticut Department of Energy and Environmental Protection (CT-DEEP) have been contacted regarding permits and regulations. A Local Notice to Mariners has been posted, and navigation buoys have been designed and purchased for compliance with CT-DEEP regulations.

Tasks remaining prior to deployment include the final testing and assembly of the scintillation system at the WHOI dock, modification of the broadband backscattering array to include identical transducers for better characterization of the spatial and temporal structure of shear instabilities, and calibration of the broadband backscattering array. All instruments will be shipped to Avery Point, CT to be loaded on the RV Connecticut. All operations will take place from the RV Connecticut, which will be on-site 24/7 and will act as a floating laboratory standing by the scintillation instrumentation.

RESULTS

There are no new results at this point in time as the field measurements have not yet been performed. The field deployment is scheduled for 29 October 2012 – 2 November 2012. All preparations for the deployment are currently on track.

IMPACT/APPLICATIONS

Increased understanding of high-frequency acoustic propagation in shallow estuarine environments characterized by strong tidal flow, high shear, strong stratification and dissipation, and increased water property variability. Assessment of the importance of anisotropy and 3-D structure of turbulence in determining acoustic propagation in these environments.

RELATED PROJECTS

None

REFERENCES

1. V.I. Tatarski, *The effects of the turbulent atmosphere on wave propagation* (National Technical information Service, U.S. Department of Commerce, Springfiled, VA. 1971).
2. S.M. Flatte, R. Dashen, W.H. Munk, K.M. Watson, and F. Zachariasen, *Sound transmission through a fluctuating ocean* (Cambridge Univeristy Press, New York, 1979).

3. Duda, T. F., S. M. Flatte and D. B. Creamer, "Modelling meter-scale acoustic intensity fluctuations from oceanic fine structure and microstructure," *J. Geophys. Res.,* 93, 5130-5142, (1988).

4. Henyey, F.S., D. Rouseff, J. M. Grochinski, S. A. Reynolds, K. L. Williams, and T. E.Ewart, "Effects of internal waves and turbulence on a horizontal aperture sonar," *IEEE J. of Oceanic Eng.*, 22, 270-280 (1997).

5. D.M. Farmer, S.F. Clifford, and J.A. Verall, "Scintillation structure of a turbulent tidal flow," *J. Geophys. Res*. **92**, 5369-5382 (1987).

6. D. Di Iorio and D.M. Farmer, "Path-averaged turbulent dissipation measurements using high-frequency acoustical scintillation analysis," *J. Acoust. Soc. Am*. **96**(2), 1056-1069 (1994).

7. D. Di Iorio and D.M. Farmer, "Two-dimensional angle of arrival fluctuations," *J. Acoust. Soc. Am*. **100**(2), 814-824 (1996).

8. D. Di Iorio and D.M. Farmer, "Separation of current and sound speed in the effective refractive index for a turbulent environment using reciprocal acoustic transmission," *J. Acoust. Soc. Am.* **103**(1), 321-329 (1998).

9. W.R. Geyer, A.C. Lavery, M.C. Scully, and J.H. Trowbridge, "Mixing by shear instability at high Reynolds number," *Geophys. Res. Lett.* **37**, L22607, (2010). doi:10.1029/2010GL045272.

10. Lavery, A.C., Geyer, W.R., and Scully, M.E., "Broadband acoustic imaging and quantification of stratified turbulence," submitted to *J. Acoust. Soc. Am.*

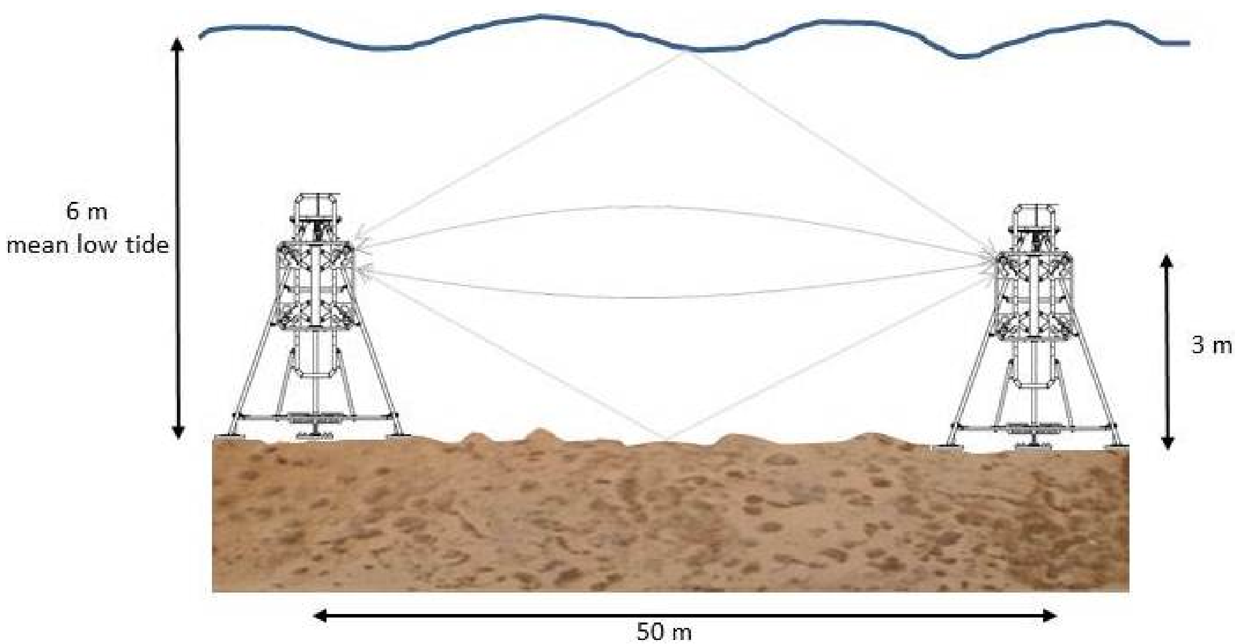

Figure 1. The high-frequency acoustic propagation system as it will be deployed in the CT River in Fall 2012. The dominant flow is in/out of the page relative to this configuration.

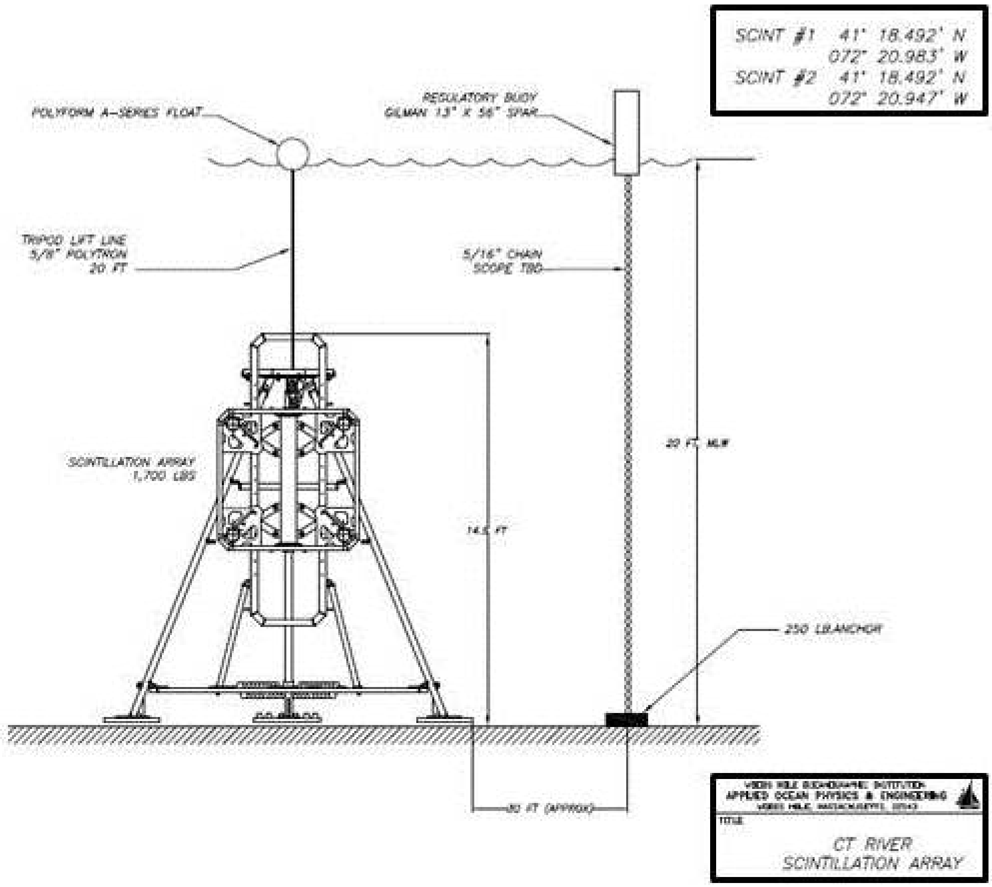

Figure 2. Schematic of one of the two high-frequency acoustic propagation/scintillation system tripods as it will be deployed in the CT River in Fall 2012. The regulatory buoy (one per tripod) required by the State of Connecticut Department of Energy and Environmental Protection for navigational proposes is shown. A small buoy directly above the scintillation system tripod is for ease of deployment and recovery.

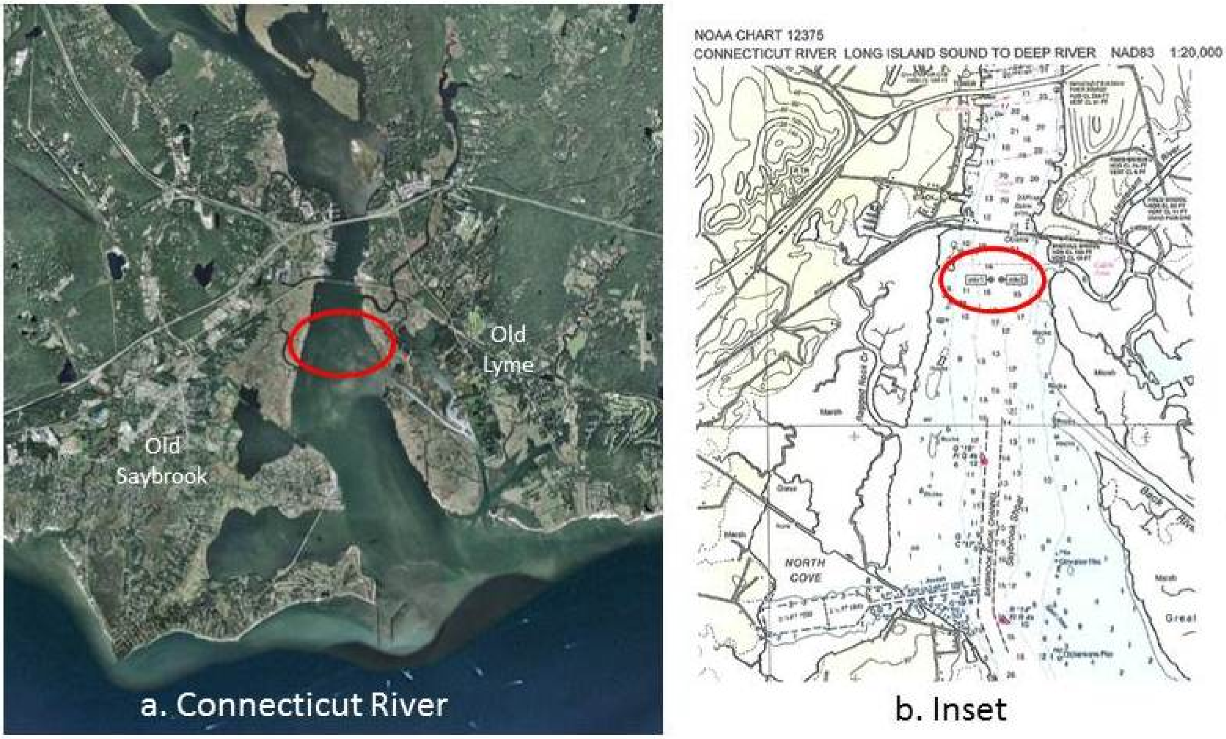

Figure 3. Location of the scintillation system deployment in the CT River estuary in Fall 2012.

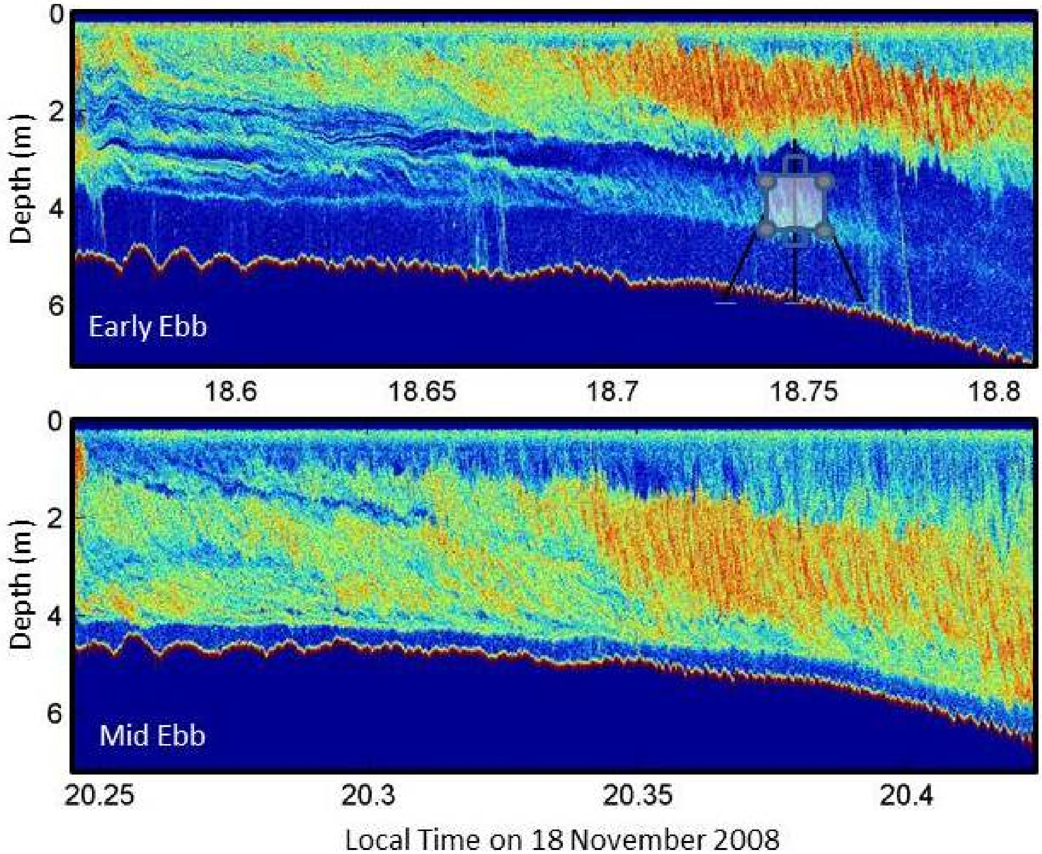

Figure 4. Broadband acoustic backscatter (220 – 320 kHz) in the CT River in November 2008 during the a) early and b) mid ebb collected at the same location as the upcoming scintillation experiment. These data were collected with the transducers pole mounted and the vessel under way. The position of the scintillation tripod in relation to the expected water-column structure is shown in a).

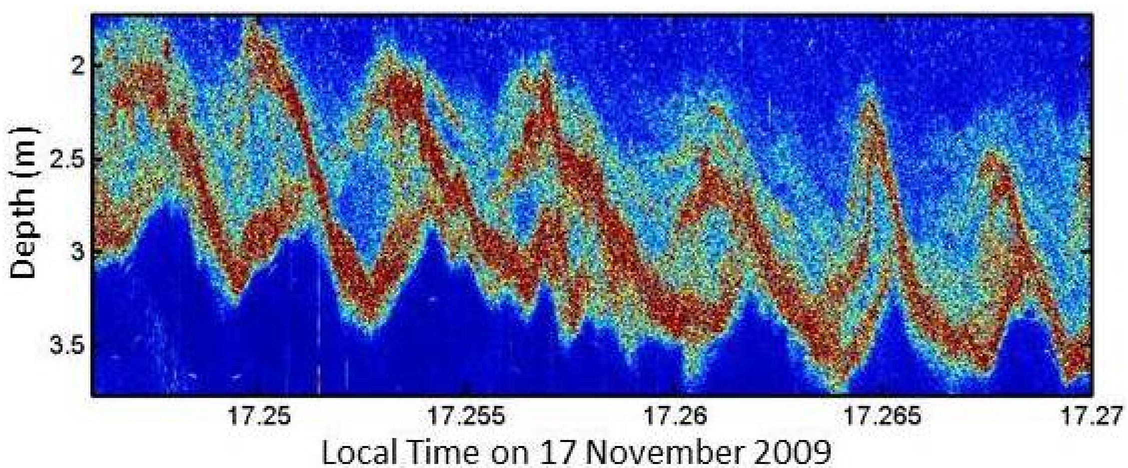

Figure 5. Typical shear instabilities observed in the CT River in November 2009 using broadband acoustic backscatter.

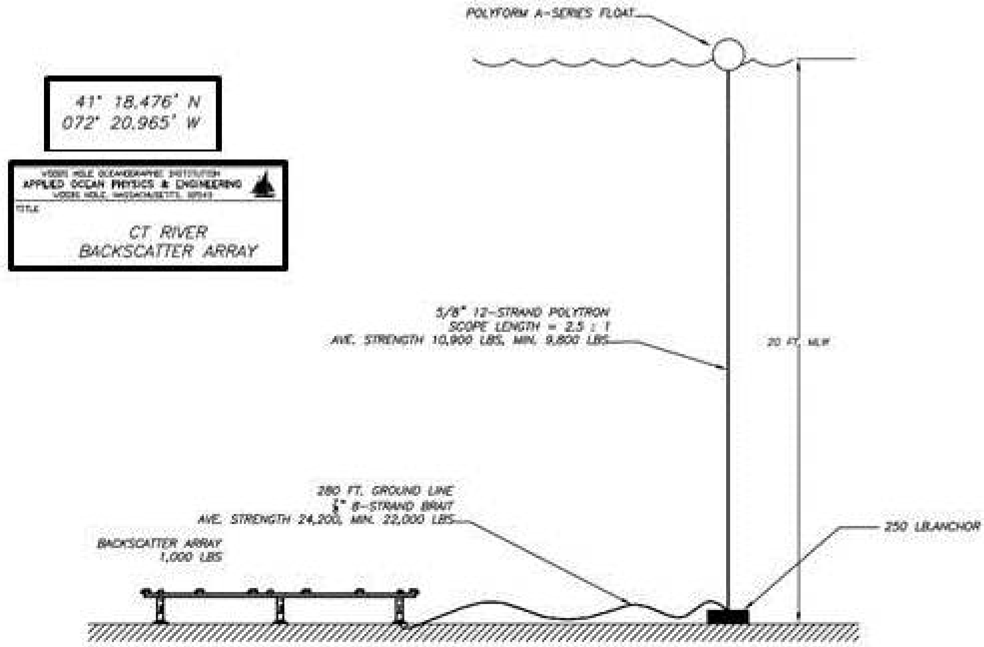

Figure 6. Schematic of the broadband acoustic backscattering array as it will be deployed in the CT River in Fall 2012 for imaging and quantification of turbulence, microstructure, and shear instabilities. The broadband acoustic backscattering array will be cabled to the RV Connecticut for real time visualization of turbulence, microstructure, and shear instabilities.